

THE DESIGN OF SPORT AND TOURING AIRCRAFT

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16. Abstract Criteria for designing sport and touring aircraft are reviewed: takeoff distance, wing surface area, mass, cruising speed, from the standpoint of marketability. Requirements related to design of sport and touring aircraft now include low fuel consumption and optimum efficiency. A computer program for calculating flight performance makes it possible to vary automatically a number of parameters-- altitude, wing area, and wingspan. Design characteristics are determined by selection of flight altitude. Three different wing profiles are compared. Potential improvements with respect to performance and efficiency are related to use of fiber composites, better propeller profiles, more efficient engines, and use of suitable instrumentation for optimum flight construction.					
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# THE DESIGN OF SPORT AND TOURING AIRCRAFT

R. Eppler\*\* and W. Günther\*\*\*

## 1. Introduction

The decision to develop a new aircraft is, after a point, /13  
irreversible for the manufacturer and possibly poses a real  
risk for him. The success of an aircraft depends extensively  
upon satisfying the market when mass production begins.

The market potential of the aircraft to be developed (which  
should be determined by good qualitative market analyses) are  
better the more attractive the aircraft is in terms of its  
performance and marketability as opposed to competing models,  
in which, of course, the traditional market base of the  
manufacturer also plays a decisive role.

Developing a new aircraft allows most manufacturers,  
through alternative designs, to comply with the market  
analyses, but, because of high development costs, not all might  
be able to follow through to the construction of a prototype.

A specific design parameter, if developed too early, /14  
may prevent eventually promising approaches from being  
developed. It is therefore important to vary as many possible  
design parameters as possible, and on the basis of these, to  
look for the optimum approach. As long as the project is in  
the outline phase, changes do not yet become more costly. What  
we mean by less than optimum will be explained later on in the  
text.

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\*Numbers in the margin indicate pagination in the foreign text.

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University of Stuttgart

Design philosophy is generally based on the same data. The craft should be developed for a variety of tasks so that tasks will be performed in the safest, most reliable, and most economical way. These alternative designs are compared to the optimum design. There is no uniform evaluation for this evaluation, including the scope of the tasks, which a decision can be based upon. The manufacturer must decide how individual tasks are to be weighed and evaluated. Depending on the importance of each, a judgment will be made in favor of one or the other. The anticipated market potential should always be the principal factor in deciding importance.

Methods of evaluation, as well as the design process, will be increasingly supported by modern computer technology. Moreover, not only is new awareness acquired, but this process often raises new problems, so that engineers' creativity and professional experience is not limited.

To avoid lowering the market potential from the start, the prospective aircraft should be both simple and progressive in comparison to existing types. In addition, it should incorporate potential for development to permit flexibility in reacting to market changes.

In this case simple should not mean primitive, but /15 rather a clear and farsighted design, as well as a new and efficient production processes.

## 2. Positive Criteria

Up to now construction of sport and touring aircraft has been based principally on the desire for

1. High cruising speed

and, as much as possible,

2. Shortest takeoff and landing distances

which increase safety and make it possible to use a greater number of runways.

Basic to the prospective market share of an aircraft is

3. Limited fuel consumption

and

4. Maximum efficiency.

The following must be applied as additional important positive criteria in the area of flight performance:

5. Maximum operating range

6. Good climbing performance

7. Cruising altitude

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8. Service-ceiling

Equally significant are

9. Good flying attributes

to lower stress on the pilot, which at the same time increases safety and efficiency.

In addition, static and dynamic stability factors are ranked as follows: direction and lateral stability, trim,

rudder efficiency and steering power, stalling flight, and diving characteristics.

As for different airplane weights, contributing factors will be taken into account so that

10. Deadweight
11. Maximum takeoff weight, which is related to
12. Additional cargo capacity and
13. Tank volume

determine maximum operating range.

In general, a beneficial aircraft layout will require:

14. High dependability
15. Prolonged durability
16. Feasible maintenance and easy servicing,

to hold down repair costs.

With regard to physical stress on the pilot, good flight attributes are important, as well as cockpit design, specifically, /17

17. Instrumentation
18. Arrangement of the controls
19. Comfort of the chair over a long period of time
20. Reliable radio and navigation equipment.

Important criteria for ground taxiing are:

21. Maneuverability and the
22. Brakes.

One cannot satisfy this wide range of standard criteria all at once. Fortunately, many of these criteria are fulfilled independently of others. For example, navigation equipment affects price and can therefore be judged solely according to its effect on efficiency since good instrument and control arrangement has little to do with speed. On the other hand, capacity factors are often influenced by certain design factors. These will be explained in the following examples. For this reason, ways to arrive at good compromises through concrete designs will be described.

### 3. Variable Parameter

The proposed aircraft is optimized with dimensions which can be changed or varied, such as geometry of wings, fuselage, and tail unit.

The airfoil is the most essential aerodynamic structural element of the airplane. Its geometry, i.e. layout and airfoil section, is variable to a large extent. It must, however, be laid out early in the planning stage. The airfoil design, which has somewhat conflicting demands, such as short takeoff and landing distance, good flying characteristics in all phases of flight, high climbing capacity and wide operating range, can then be implemented, but only by integrating wing geometry into optimum harmony, if the effect of change in wing geometry on wing capacity and efficiency is known. Wing geometry can be varied within the following parameters:

1. Airfoil sections
2. Wing dimensions

3. Wingspan, which, through changes in the wingspread, in this case, wing depth, can be changed simultaneously or separately

4. Tapering off point

5. Distortion

In addition to takeoff criteria, parasitic and induced drag are strong influences on capacity factors. These effects are not always clear, as in the case of parasitic drag, which is really parasitic throughout. An increase in wingspan for the same area can, nevertheless, improve cruising speed and, due to higher stress, enlarge takeoff distance. A computer program is necessary to account exactly for these influences, as has already been mentioned. This program computes an airplane's soaring performance polar diagram (speed polar), in this case, for a version of an airplane. In addition, following data will be obtained:

a) Cruising speed

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In the calculating program,  $N_0$  represents 75% of available capacity at sea level. In this case, maximum available capacity at cruising elevation is less than  $0.75 N_0$ . For the decline in capacity as altitude drops, the formula given by U. Hutter will be used,

$$N = N_0 (\rho / \rho_0 - 0.15) / 0.85$$

if no exact engine data is available. For propeller efficiency,  $N=0.7$  will be accepted.

b) Climbing speed

Calculations of available capacity and propeller efficiency



will be as valid as cruising speed calculations for the respective altitudes.

c) Takeoff distances

Take off distances will be calculated for grass and paved runways, and will introduce two very different coefficients of friction,  $\mu_1$  and  $\mu_2$  into the calculation. Also, a sequence of hypotheses applied equally to all aircraft will be necessary to determine takeoff distances, so that the effect of the most important parameter remains clear.

As we know, propeller thrust increases with airplane speed. Standing thrust will be calculated with 70% standing thrust efficiency. Along with takeoff speed ( $1.05 \cdot v_{\min}$ ), thrust will be determined from ray theory and multiplied by 0.7. A linear interpolation occurs between standing and takeoff thrusts. Acceptance of strain reduction in wheels through the airfoil lift during takeoff, along with accompanying reduction in friction, was the most difficult requirement to meet.

Therefore, takeoff stress on the wheels and lift will /20 be shared. The declining portion  $G_r$  of takeoff stress yields the frictional power  $\mu \cdot G_r$  on the wheels. Wind resistance  $W = (C_w/C_a) \cdot A$  is combined with lift,  $A$ . Simplified hypothesis  $C_w/C_a = \mu$ , means that, during takeoff, there is an effective amount of glide, which is equal to the amount of ground friction. There is a simple formula with which somewhat shorter takeoff distances can be calculated, under the recurring hypothesis that there is no lift during rolling. This assumption make it possible to arrive at a realistic rolling distance. Resistance coefficient,  $C_w$ , does not enter into the result. For this

reason, aircraft which reach glides higher than the respective amounts of friction during rolling are easily at a disadvantage compared to other aircraft. Most of the time the starting angle and coefficients  $C_A$  and  $C_W$  for the rolling procedure are not known, so that a hypothesis little better than the previous can be found.

On standby, the fixed computer program makes it possible to estimate flight capacity beforehand, as well as automatic variations of altitude parameters, wing surface area, wing spread and parasitic drag, to name the most important factors. Due to the wealth of data available, all parameters will not be varied at the same time.

Automatic variations in wing surface area and wing spread resulting from their enlargement can be used to calculate additional stress levels. In addition, the larger tail unit area can be considered along with the parasitic drag.

The program will derive stress  $C_{ws} \cdot F$  from parasitic drag.  $C_{ws}$  automatically adjusts to a change in wing surface area.

Induced drag is calculated from the well-known formula, /21

$$C_{W1} = C_A / \pi \lambda \cdot (1 + \delta)$$

$\lambda$  is wingspan, and  $\delta=0$  represents the case of an elliptical liftoff distribution. The factor  $\delta$  must be put into the program for each calculation.

Likewise, coefficients  $C_A$  and  $C_W$  of the selected airfoil sections must be put in for each Reynolds number. The middle Reynolds number for every  $C_A$  will be established from

these, as well as through interpolation of the corresponding  $C$ . An eventual wing point is disregarded.

Motor capacity  $N_0$ , in this case for different altitudes, and propeller diameter  $D$  will likewise be put into the program.  $D$  is moreover only included in standing thrust and takeoff distance.

Of course, airfoil section and motor data vary, but certainly not automatically. Old data is replaced beforehand with new data.

The first example of program application serves to clarify the often-posed question of how takeoff distance increases if takeoff dimensions increase. This should be clarified as soon as possible, for on the one hand, the frame often becomes heavier than expected, and on the other hand, we are always interested in raising loading capacity and fuel capacity and in introducing additional instruments. All of this is usually not a particular problem with regard to aircraft stability. It is preferable to hold out for the least decisive positions with some margin of stability. Also, plane cruising capacity will hardly be influenced by dimensions.

If the aircraft is to be used only for travel, the wings could be considerably smaller. They are constantly hindered by a large wing section, which is only necessary for takeoff and landing. Because they can be only poorly flown without both these phases, each must be kept in mind. If stability is maintained through higher mass, this should also be done on the runway. One can try to reduce takeoff distance by enlarging wing surface area or wingspan can be varied and the  $C_{A \max}$  of the wings can be increased, as, for example, when the aileron is turned down somewhat symmetrically in the

takeoff position of the landing flap.

The result of a typical calculation is represented in figures 1 and 2. It can serve for a small sport and touring aircraft. Motor capacity is 120 hp and propeller diameter is 1.83 m. Takeoff dimension  $M_0$  serves for a wingspan of 10 m and a 13 m<sup>2</sup> wing surface area. Aircraft weighing 850 and 950 kg would be selected. Wing surface area and wingspan would vary at that moment. For each additional 1 m<sup>2</sup> of wing surface area, 10 kg of mass, and 1 m of wingspan, 8 kg of mass is lost. Takeoff distances would be calculated at sea level and at 1,500 m altitude for grass and paved runways.  $C_{A \max}$  depends from the start on the Reynolds number. The results in figures 1 and 2 are easy to understand. Runway distance decreases as wing surface area increases, but not so much as to simultaneously increase mass. The wing span hardly has any effect, while the effect of aerodome level and mass,  $m_0$ , is critical.

It is also of interest here how climbing speed will be affected by the same variations. This is represented in figures 3 and 4. The figures show that wingspan has a positive effect, while area, on the other hand, has a negative /23 effect. If one is interested in a high service ceiling or towing plane, wingspan should not be restricted.

Another important design question is the landing flap system. We can achieve a higher  $C_{A \max}$  through the Fowler flap than through the usual Wölb flap. Also, symmetric deflection of the aileron in takeoff position can be immensely helpful. In figure 5 the effect of the  $C_{A \max}$  at the runway is depicted. It is significant. An increase in  $C_{A \max}$  from 1.65 to 1.91 makes possible 55-65 kg more takeoff mass on the same runway.

Assessing calculated touring speed, which plays a dominant role in efficiency, represents a special problem. In this case, the estimate placed on the altitude yields different wing requirements, which are obtained specifically by using a laminated airfoil section. At the poles of the laminated airfoil sections, which will be described later, it is easy to recognize the  $C_A$  region, in which the top side and underside of the wings possess a laminated drift and the fact that the so-called laminated yard depends on the Reynolds number. The higher the Reynolds number, the smaller the laminated yard. In the polar diagram, its lower boundary shifts to the top and the upper boundary to the bottom.

A touring craft should naturally make use of the lamination effect. Lift coefficient  $C_{Ar}$  of a touring craft, which is usually the smallest design coefficient, should lie at the lower boundary of the lamination yard. Figure 6, for example, represents  $C_{Ar}$  and  $Re_r$  as a function of altitude. We recognize a decrease in Reynolds number for a touring craft and an increase in lift coefficient with altitude. The higher the touring altitude, the higher the lower boundary of the laminated yard and this laminated yard can be even wider. Due to both these influences, the upper boundary of the laminated yard will lie higher. Accompanying this is an increase in the maximum lift coefficient, which results in a positive takeoff.

The lamination effect on the touring craft near the /24 ground is abandoned, so that a higher  $C_{A \max}$  can be achieved with the same design. This produces lower takeoff distances. If this is not required, the wing surface area could be smaller. It would seem that wing surface area, together with the effects of gravity and resistance, plays an important role. The exact altitude from which to evaluate the touring

craft must be considered. In the following examples, this is done for an elevation of 3000 m. There is, likewise, a further reason to assign the touring craft an altitude that is not too low. Relatively fast aircraft will be flown mostly in gusts at higher elevations. In normal thermals the plane could not be flown out of the gusts because of the weight of the passengers.

After these general considerations we can now compare different airfoil sections.

Three different airfoil sections have been chosen, which are all about the same width, have the same momentum coefficients, and are supplied with normal Wölb flaps as landing aids. /25

The first airfoil section, indicated as 1211, is a typical airfoil section as it would be developed for applications in conventional construction with rough upper surfaces (rivets, aviation, etc.) [1]. Figure 7 contains an outline of the airfoil section and its speed distribution. It can be seen that on the upper and lower sides of the airfoil section near the nose, the maximum speed corresponds with the minimum pressure. These speed distributions have proven to be favorable, however, where the laminar boundary layers are abandoned. This allows reaching high lift coefficients, which make possible a reduction of the wing surface area. Likewise, with a calculated program, polar diagrams of airfoil section 1211 with a rough upper surface (shown by  $r=1$ ) are seen in figure 8 for  $Re = 2 \cdot 10^6$ ,  $5 \cdot 10^6$ , and  $9 \cdot 10^6$ . In the same figure, the polar diagrams for a smooth upper surface area are represented by half of the total for the same Reynolds number. It can be seen that the resistance coefficient with a smooth upper surface area will not be substantially diminished, which is plausible from the design of this airfoil section.

Nevertheless, there appears a noticeable increase in the maximum lift coefficient.

A little advice on the assessment of the theoretical polar diagrams. The program to determine the poles is described in detail in (2) and (3). After many comparisons with experiments, it is at least possible to assert that this program for comparing varying airfoil sections is the same for wind tunnel measurements. On the right side of the figure for the theoretical polar diagrams, the developments for  $C_a(\alpha)$  and  $C_m(\alpha)$  as well as the boundary layer transition and the boundary layer separation, are again made dependent on  $C_a$ . This is the same representation as is usually seen for wind tunnel measurements. The final named lines are shown here as smaller in the foreground.

The second airfoil section to compare, with the number 26 789, is a moderate laminar airfoil section. Its form and speed distribution are represented in figure 7 and its polar diagrams for rough and smooth upper surface areas in figure 9. The upper side of this airfoil section can be reached only in an area of 25%-35% of the depth of a laminar boundary level. This can be recognized from the maximum speed shown in figure 7 and from the change in lines in figure 9. For the smooth upper surface area, on the other hand, a laminar boundary level is expected of up to about 60% of the depth of the airfoil section. Due to the moderate progress of the laminar boundary layer, good maximum lift, which compares a bit to that of the 1211 airfoil section, will also be attained with a rough upper surface area.

The third airfoil section, 764, which is shown in figure 10, is an "extreme" laminar airfoil section. Through smooth

upper surface area, it achieves a minimum resistance coefficient of 0.0035 because the boundary layer stays on the upper airfoil section and on the underside between 60% and 75% of the depth of the laminar airfoil section. Since here the laminar depression depends heavily upon the Reynolds number, the ratios would also be calculated using  $Re = 7 \cdot 10^6$ . The maximum lift is not too high on the smooth upper surface area; it becomes, of course, hardly worse on a rough upper surface area.

An important question is posed for the design engineer: which of these profiles, besides the existing ones, best corresponds to his test set-up. Up to now, a comparison using the example of a three-seater touring craft has been made. Fuselage and propulsion are assumed to be given. The propulsion plant, with 96-kW capacity, drives a propeller with a 1.83-m diameter. The parasitic drag area will be applied with a wing surface area of  $15 \text{ m}^2$  by  $0.098 \text{ m}^2$ . This is a relatively good value, which cannot be reached without retracting landing gear. The extra factor for the induced drag will be taken unchanged at  $\delta = 0.1$ .

In the resulting version with  $15 \text{ m}^2$  of wing surface /27 area, a maximum aircraft weight of 900 kg will be used. It is clear that this is a fictitious example for the purpose of describing the program. By actual design practice, real data must naturally be inserted. The comparison is made using two important pieces of data. Since takeoff is an important attribute of an airplane, takeoff distance is taken from adverse conditions. Takeoff must be, if possible, at high altitude in the rain. Therefore, for this, a rough upper surface area and an altitude of 1500 m above sea level must be used. As a second essential parameter, cruising speed will be chosen at an altitude of 3000 m. It was established in the



last section how especially important high altitude is.

Maximum lift coefficient  $C_{A \max}$ , which is especially important to takeoff distance, would be calculated as the average between descents without plain flaps-deflection and with plain flaps in takeoff position ( $10^\circ$  or  $12^\circ$ ). It will be further assumed that plain flaps cover over 60% of the wingspan and that ailerons will not be obstructed. For airfoil sections 1211 and 789, a  $C_{A \max} \sim 1.65$  was sometimes produced for a rough upper surface area; with section 764  $C_{A \max} \sim 1.45$ . The exact value depends upon the respective Reynolds number.

A better, or more reliable, comparison of cruising speed is possible only using the same takeoff distance. It would therefore happen that, in all cases,  $F_o \cdot C_{A \max}$  (rough) were similar overall on the "fast" airfoil section of the wing surface area  $F_o$ . It will naturally be taken into account here that, with a larger surface area  $F_o$ , mass at  $10 \text{ kg/m}^2$  increases. To recognize the influence of wing surface area on takeoff rolling distance and cruising speed, we will increase surface area for each airfoil section by about  $1 \text{ m}^2$  or  $2 \text{ m}^2$ . The result is given again in figure 11. The reduction of cruising speed and rolling distance as surface area increases is in all cases about the same. Due to a rough upper surface area, airfoil sections 1211 and 789 are roughly /28 equivalent at take-off. Due to the smooth upper surface area, airfoil section 1211 has about 10 km/h more cruising speed and 30 m less rolling distance. This reduced rolling distance can hardly be estimated, if one also wants to allow a takeoff in the rain. Airfoil section 789 makes possible 20 m less rolling distance and 22 km/h more cruising speed.

The extreme laminar airfoil section 764 deserves a special discussion. Even with an increased surface area of  $2.07 \text{ m}^2$ ,

it uses 16 m more rolling distance in the rain. With the increase in surface area, an equivalent increase in mass is obtained. In order to bring an aircraft with this airfoil section to the same takeoff distance as airfoil section 789, surface area must be enlarged by  $1.5 \text{ m}^2$ . In this case, 764's cruising speed with a smooth upper surface area will always be 10 km/h higher than the airfoil section 789's obtainable cruising speed.

Of course if one considers the hereto necessary  $3.5 \text{ m}^2$  more surface area, and likewise expects the extreme laminar airfoil section 764's adverse flight characteristics, the tendency is then to understand how we can accomplish the construction in the area of the 798 airfoil section, thereby working with fewer extreme laminar airfoil sections.

#### 4. Conclusion

Special attention was given to airfoil sections in the preceding section, because in recent years it has been recognized that flight performance has essentially improved through use of new airfoil sections. This does not apply only to small sport and touring craft; larger aircraft in the higher price range also show potential for development in this direction.

Only the most important variable parameters, which are expected to improve performance in the near future, are mentioned here.

1. Fiber composites - The advantages of this material will first affect carrying capacity if the primary structure (wings, fuselage) is also manufactured almost exclusively from this

material and construction carried out with compatible fibers. The aircraft manufacturer is presently confronted with the fact that a necessary volume of the material is not yet available for his use.

2. Propeller - Newer investigations have concluded that the propeller, like the airfoil, can still be developed through the use of better airfoil sections.

3. Engines - A comparison of the aircraft's motors with modern vehicle engines allows the conclusion that, here too, something can be done to lower fuel consumption; for example, increased speed and compression, smaller cylinder displacement, improved propellant injector system, etc.

4. Instruments - In civil aircraft construction, notable changes in control apparatus will affect sport and touring aircraft. They will provide essential relief for the pilot and place him in the position to fly in all flight phases of the aircraft under optimum conditions.

The efforts of aircraft manufacturer in the early stage show that these unsolved problems are being faced and practical solutions sought.

## REFERENCES

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3. Eppler, R. and Somers, D. M. "Supplement to: A Computer Program for the Design and Analysis of Low-Speed Airfoils." NASA Technical Memorandum 81862. December 1980.

Key:

a) = runway (m)

b) = wing surface  
( $m^3$ )

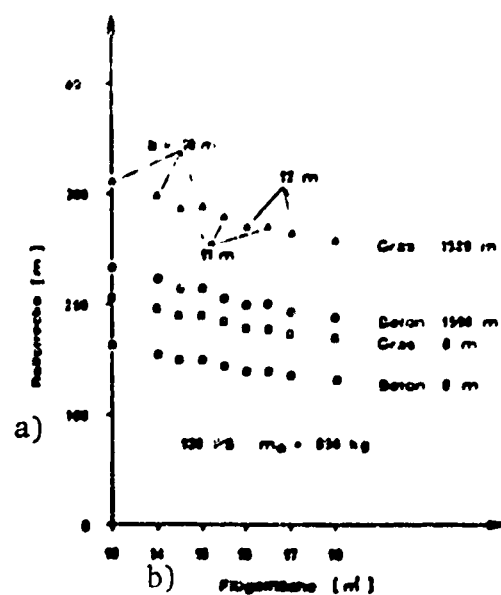


Figure 1 - Takeoff rolling distance for an aircraft with takeoff mass of 850 kg.

Key.

a) = runway (m)

b) = wing surface ( $m^3$ )

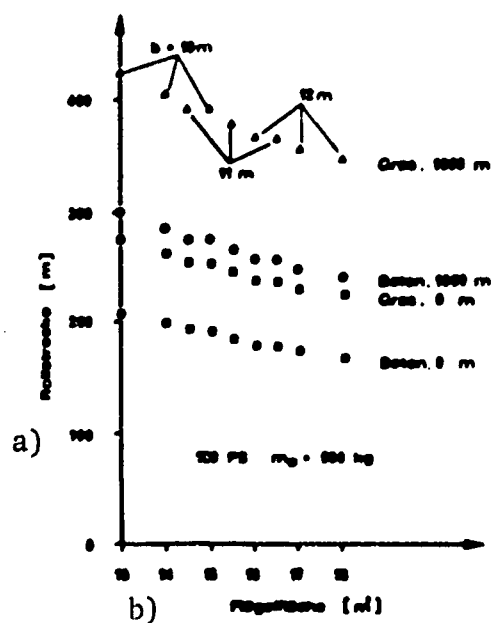


Figure 2 - Takeoff rolling distance for an aircraft with takeoff mass of 950 kg.

Key:

a) = climbing speed  
(m/s)

b) = wing surface ( $m^2$ )

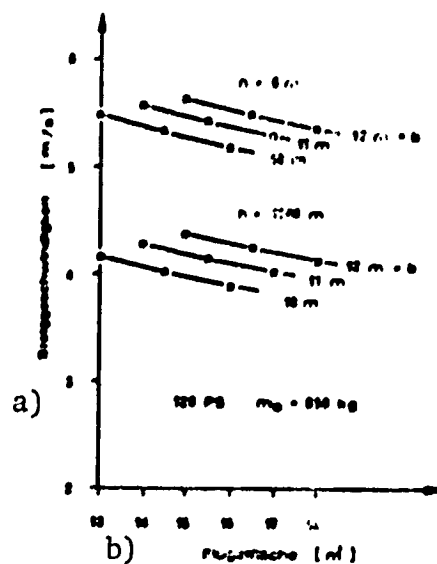


Figure 3 - Climbing speed for an aircraft with a takeoff mass of 850 kg.

Key:

a) = climbing speed  
(m/s)

b) = wing surface ( $m^2$ )

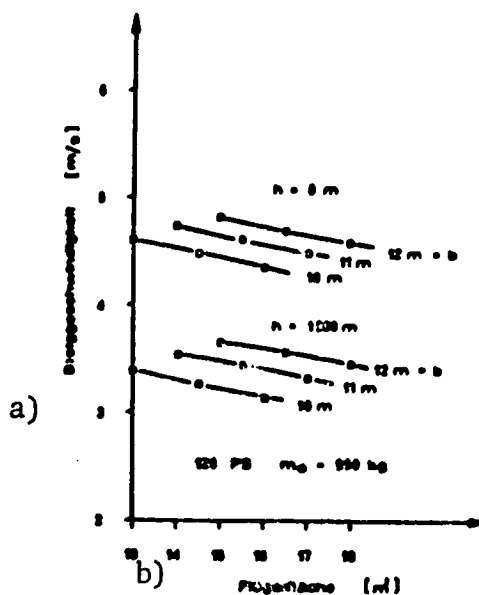


Figure 4 - Climbing speed for an aircraft with a takeoff mass of 950 kg.

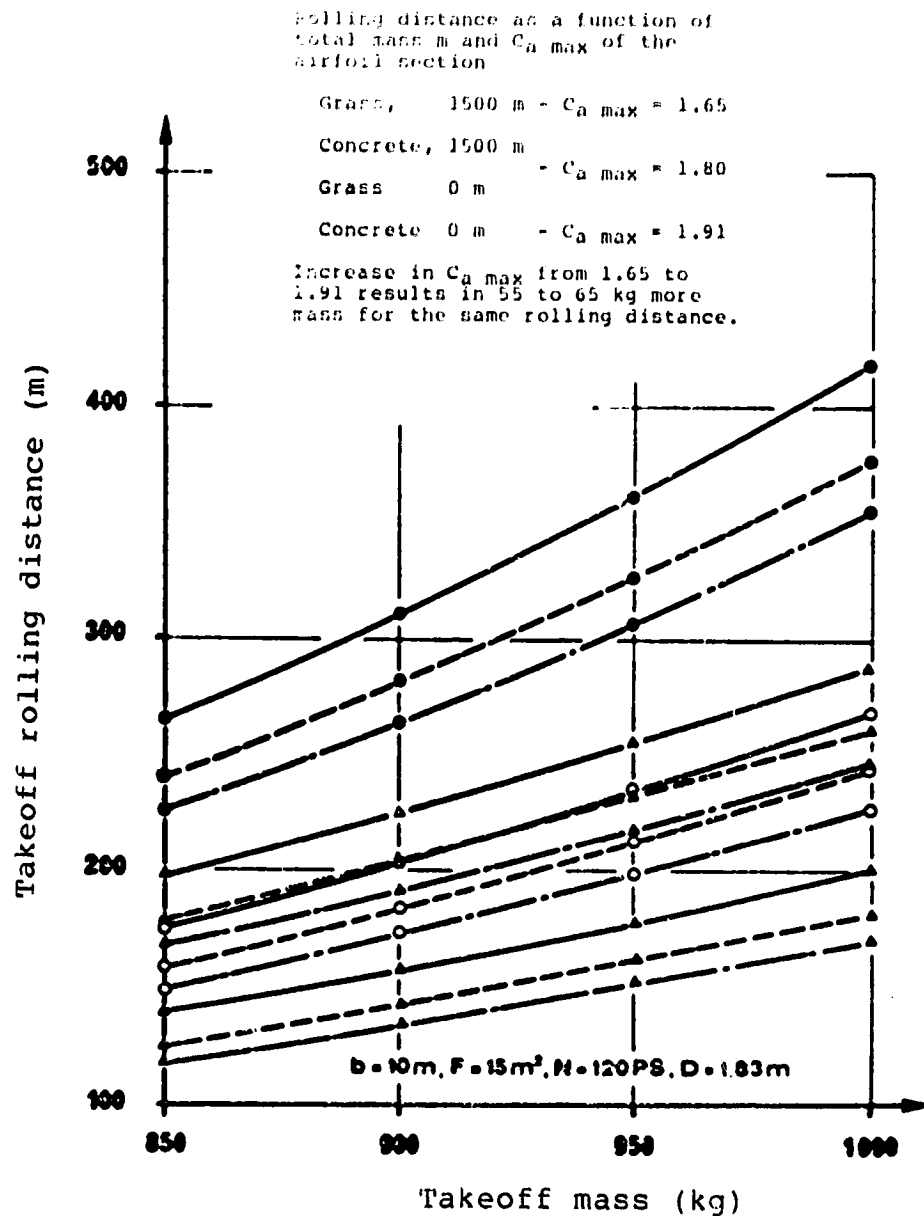


Figure 5 - Takeoff rolling distance as a function of takeoff mass and lift coefficient.

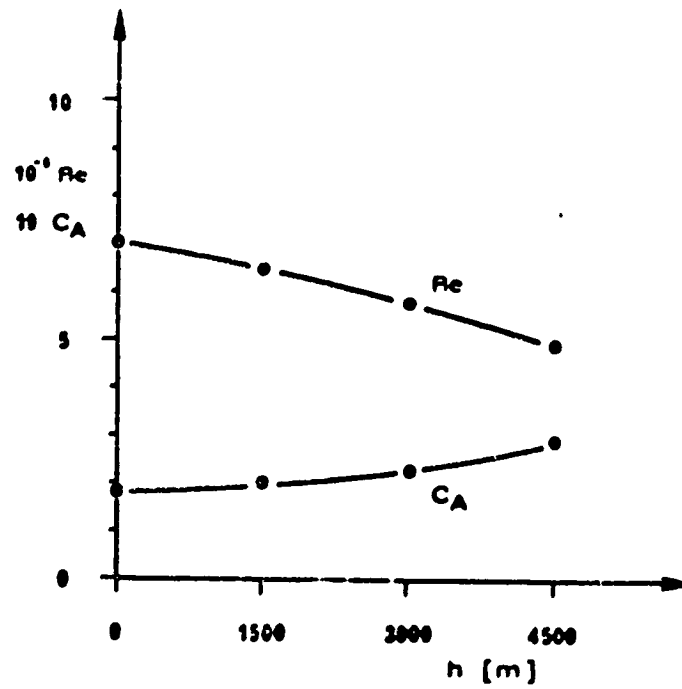


Figure 6 - Reynolds number and lift as a function of cruising level for a hypothetical aircraft in flight.



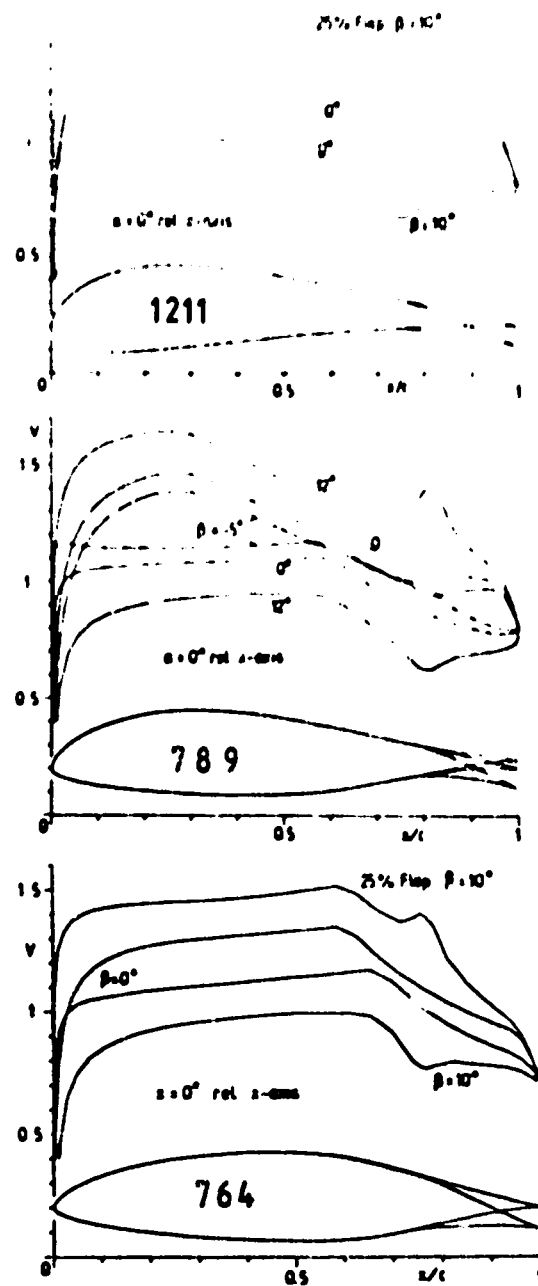


Figure 7 - Thickness and speed distribution of three airfoil sections with plain flaps.

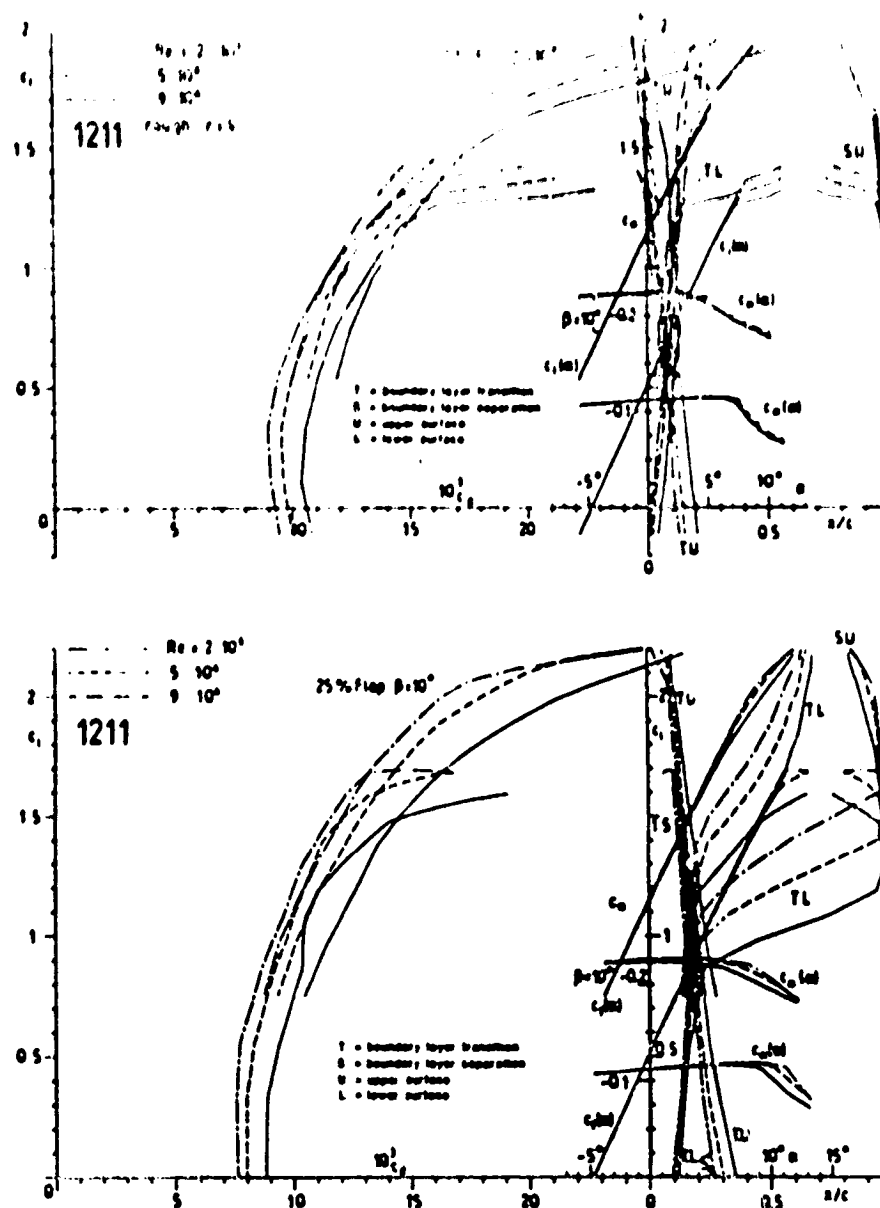


Figure 8 - Polar diagrams of airfoil section 1211 for rough and a smooth upper surface areas.

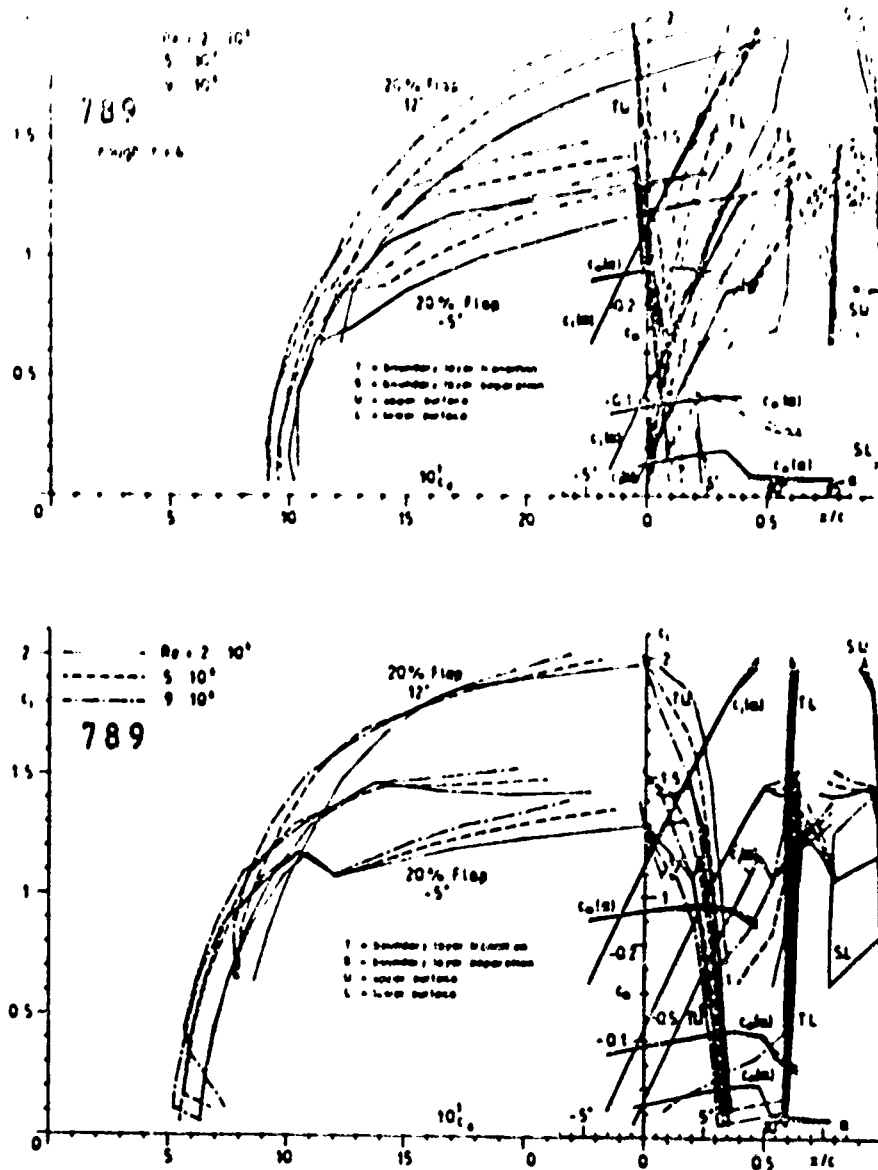


Figure 9 - Polar diagrams of "moderate" laminar airfoil section 789 for rough and smooth upper surface areas.

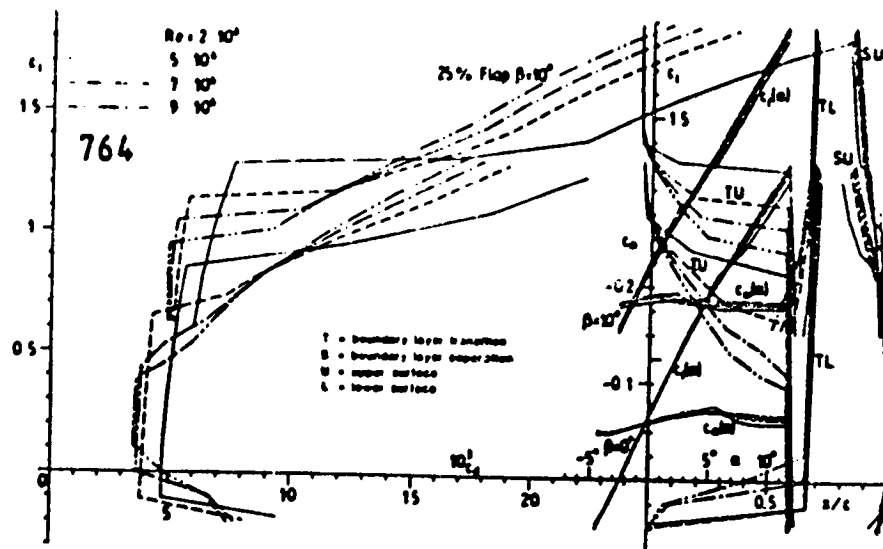
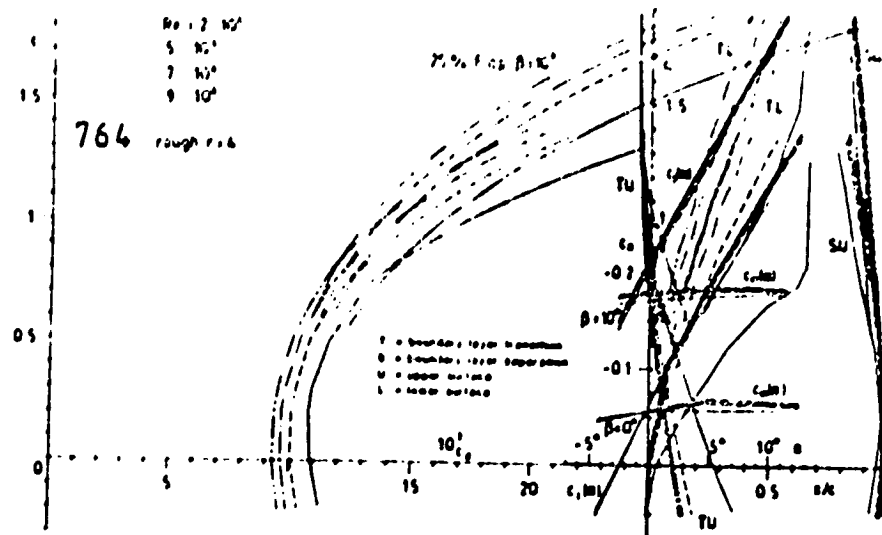


Figure 10 - Polar diagrams of "extreme" laminar airfoil section 764 for rough and smooth upper surface areas.

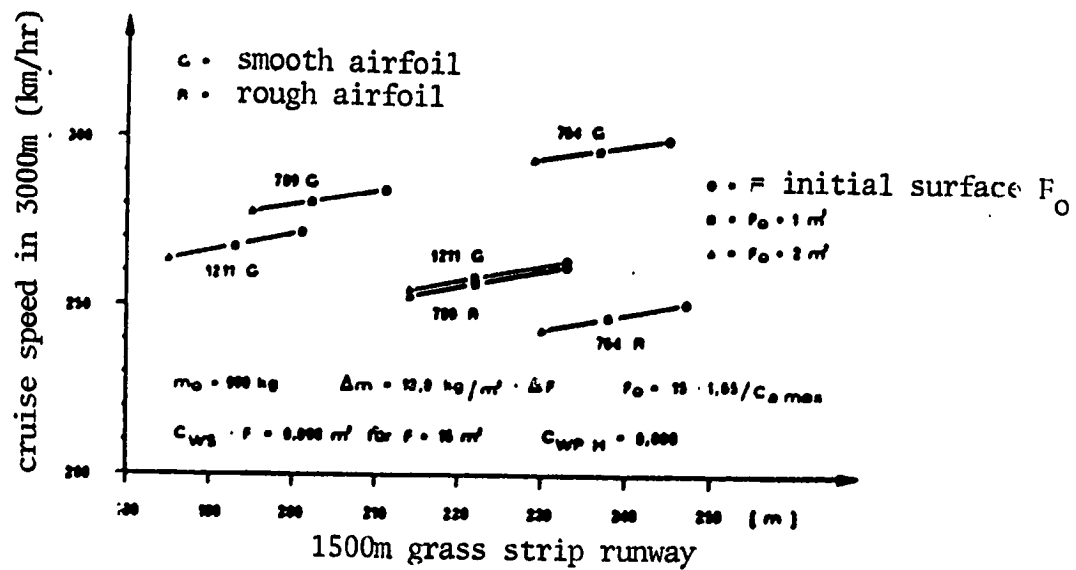


Figure 11 - Effect of airfoil section characteristics on rolling distance and cruising speed of an aircraft with lift mass of 900 kg and wing surface area of  $15 \text{ m}^2$ .